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Functional Land Management for managing soil functions: A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland

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ABSTRACT

Globally, there is growing demand for increased agricultural outputs. At the same time, the agricultural industry is expected to meet increasingly stringent environmental targets. Thus, there is an urgent pressure on the soil resource to deliver multiple functions simultaneously. The Functional Land Management framework (Schulte et al., 2014) is a conceptual tool designed to support policy making to manage soil functions to meet these multiple demands. This paper provides a first example of a practical application of the Functional Land Management concept relevant to policy stakeholders. In this study we examine the trade-offs, between the soil functions 'primary productivity' and 'carbon cycling and storage', in response to the intervention of land drainage systems applied to 'imperfectly' and 'poorly' draining managed grasslands in Ireland. These trade-offs are explored as a function of the nominal price of 'Certified Emission Reductions' or 'carbon credits'. Also, these trade-offs are characterised spatially using ArcGIS to account for spatial variability in the supply of soil functions.

To manage soil functions, it is essential to understand how individual soil functions are prioritised by those that are responsible for the supply of soil functions – generally farmers and foresters, and those who frame demand for soil functions – policy makers. Here, in relation to these two soil functions, a gap exists in relation to this prioritisation between these two stakeholder groups. Currently, the prioritisation and incentivisation of these competing soil functions is primarily a function of CO_2 price. At current CO_2 prices, the agronomic benefits outweigh the monetised environmental costs. The value of CO_2 loss would only exceed productivity gains at either higher CO_2 prices or at a reduced discount period rate. Finally, this study shows large geographic variation in the environmental cost: agronomic benefit ratio. Therein, the Functional Land Management framework can support the development of policies that are more tailored to contrasting biophysical environments and are therefore more effective than 'blanket approaches' allowing more specific and effective prioritisation of contrasting soil functions.

Introduction

The challenge for agriculture – food security and the environment

A growing global population and dietary changes are amongst the factors that are fuelling a demand for increased agricultural output (Godfray et al., 2010). Increasing demand places urgent and growing pressure on soils to support the intensification of agriculture, which is an essential component of food security (RSC, 2012). The productive capacity of soils is diminishing and has already diminished in many parts of the world and there are limited opportunities for land expansion (Wild, 2003). Thus far, agricultural intensification has been very effective at achieving increased production. Production increases of 115% between 1967 and 2007 have been achieved on modest land area increases of approximately 8% (Foresight, 2011). However, a further increase

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in productivity is likely to be associated with additional stress on the natural resource base. Whilst not synonymous, in many cases intensification has been accompanied by unsustainable environmental impacts such as biodiversity loss and the use of resources such as inorganic nitrogen, phosphate fertiliser, fuel use, and water (Foresight, 2011; UK NEA, 2011). Concerns about these deleterious impacts have stimulated a societal demand for improved environmental sustainability. Consequently, the agricultural industry along with increasing productivity is also expected to meet increasingly stringent environmental targets. Within the European Union (EU), environmental targets include inter alia targets such as those under the Sustainable Use Directive (2009/128/EC) (EU, 2009a) and the Water Framework Directive (2000/60/EC) (EU, 2000) that requires that water bodies be of good ecological status. In Ireland, the Nitrates Directive (91/676/EEC) is the agricultural programme of measures (POM) that sets out a regulatory framework for nutrient management (EU, 1991) to achieve this status. Also, the Habitats Directive (92/43/EEC) (EU, 1992), Birds Directive (2009/147/EC) (EU, 2009b), and EU EIA Directive (2011/92/EU) (EU, 2012) through Natura 2000 seek to halt the loss of biodiversity. In summary, the world needs more food (Godfray et al., 2010), notwithstanding this, agricultural development cannot be intensified beyond the carrying capacity of soils, ecosystems and the socio-economic environment (Mueller et al., 2011).

In this context, ecosystem services are the benefits that people obtain from ecosystems and include the attributes and processes through which natural and managed ecosystems can sustain ecosystem functions (MA, 2005). Many ecosystem services rely on soils and land use for their delivery (Bouma, 2014). These include provisioning services such as food and water, regulating services such as disease control, cultural services and supporting services such as nutrient cycling (Haygarth and Ritz, 2009). This subset of ecosystem services, hereafter soil functions, are described in the Thematic Strategy for Soil Protection (EC, 2006), and these define the role of soils in the contribution to ecosystem services (Bouma, 2014). Although the concept of ecosystem services has been extensively studied and reviewed (Abson et al., 2014), there are a lack of tools to understand and manage multifunctional landscapes (O'Farrell and Anderson, 2010). A major challenge exists in how to satisfy all demands on land and soil simultaneously, particularly as these are often competing demands. The demand for solutions that support the co-existence of environmental sustainability with increased food outputs has prompted the development of the Functional Land Management framework (Schulte et al., 2014).

Functional Land Management

Functional Land Management seeks to optimise the agronomic and environmental returns from land and relies on the multifunctionality of soils. This framework focuses on five soil functions that are specifically related to agricultural land use: (1) Primary production; (2) Water purification and regulation; (3) Carbon cycling and storage; (4) Functional and intrinsic biodiversity, and (5) Nutrient cycling and provision (Bouma et al., 2012; Schulte et al., 2014). Although soils are multifunctional, the heterogeneity of soils means that soils will vary in their relative capacity to deliver individual soil functions which means that challenges to sustainability will vary spatially based on location. Ultimately, the suite of soil functions that a soil provides depends on both land use and soil type. To meet the challenge of the sustainable intensification of agriculture, Functional Land Management seeks to optimise the suite of soil functions that it provides by matching the supply of soil functions with demand (Schulte et al., 2014). For example, the demand for the soil function 'Water purification' is framed by the Nitrates Directive, which requires groundwater nitrates concentrations to be maintained below 50 mg l^{-1}, through denitrification of (part of) the nitrogen surplus. To present the delivery of soil functions, Schulte et al. (2014) used Ireland as a case-study. Importantly, Functional Land Management is not designed as a tool for zoning, but for use at a scale that can consider what Benton et al. (2011) refer to as the net landscape effect across all affected land.

Case study: agriculture in Ireland – trade-offs between two soil functions

Ireland's response to the global imperative of food security is captured in the *Food Harvest 2020* strategy. *Food Harvest 2020* is the industry-led roadmap for agricultural growth in Ireland. The abolition of the EU milk quota in 2015 is a prime driver that will allow farmers to increase their dairy output. As a result, the roadmap foresees a volume increase target of 50% for the dairy sector by 2020, in contrast to the targets for other agricultural sectors, which are value based (DAFF, 2010). The dairy volume increase target for the dairy sector requires a level of intensification, expansion or augmented resource use efficiency, to be achieved. All targets under *Food Harvest 2020* aim to both intensify output whilst concurrently reducing the environmental footprint of production. For example, a target of increasing dairy production by 50% will simultaneously seek to reduce greenhouse gas (GHG) emissions for every litre of milk produced and provide sustainable returns (DAFF, 2010).

Ireland has a temperate maritime climate which means that it has a natural advantage in relation to grass growing potential. Ireland's success as a major milk producer globally relies on its grass based system and it is this low-cost system that provides Ireland with its competitive advantage. In general, the volatility of agricultural input prices, such as fertilisers or concentrates, requires producers to adjust to minimise this impact on their profitability (Donnellan et al., 2011). In Ireland, whilst a grass-based system allows producers a level of insulation against these input price fluctuations, seasonality and lower yields can represent a challenge not associated with intensive concentrate based systems (Donnellan et al., 2011). Amongst other measures, improved grass utilisation and extending the grazing season are essential to the continued success and competitiveness of the Irish dairy sector. Furthermore, in relation to GHG emission, temperate grass-based systems like Ireland and New Zealand have the lowest emissions per unit fat and protein-correct milk when compared to tropical and arid grassland systems (Teagasc, 2011a). Thus, to reduce the potential of carbon (C) leakage associated with dairy production, the environmental rationale to optimise production in temperate grass-based systems, such as in Ireland, exists.

In North Atlantic maritime climates, however, excess soil moisture is a key constraint to achieving these twin targets, as it simultaneously constrains primary productivity and increases the risk of negative environmental impacts (Schulte et al., 2012). Wet soils are easily damaged and so their ability to deliver soil functions can be compromised. Surface compaction and subsurface compaction have been identified as major threats associated with the climatic regime of North Atlantic Europe related to the trafficking or working of soil under inappropriate soil moisture conditions (Creamer et al., 2010). Wet soils have lower load-bearing capacity and grazing damage can lower herbage production by 20% or more (Humphreys et al., 2011). Furthermore, Schulte et al. (2006) demonstrated that the length of the grass growing season can be reduced by as many as five months at a regional level as a result of excess soil moisture conditions. Overall, wet soil conditions are considered the most important factor limiting the utilisation of grazed grass on Irish farms (Shalloo et al., 2004; Creighton et al., 2011).

In this setting, land drainage systems on existing land in production or on new land areas that fulfil EIA criteria, offer potential as part of a suite of measures to overcome such constraints. Any land drainage works aim to siphon excess water from the soil and

Fig. 1. Freestyle illustration of typical suites of soil functions under contrasting land use types.

Schulte et al. (2014)

maintain the water table at a designated depth below the rooting zone, thereby increasing soil water storage capacity. Primarily from a farm management perspective such an investment improves trafficability for machinery and livestock as the recovery time after episodic rainfall events is shorter (Tuohy et al., 2014). The average cost of milk production is reduced by over 1 € cent/l for a 2.5% increase in grazed grass in the cow diet where the diet of the cow is comprised of more than 50% grazed grass (Dillon et al., 1995; Lapple et al., 2012). Therefore a key objective for land drainage design is to extend the grazing season. The extent of land drainage in Ireland of the utilisable agricultural area is currently low at 25%, relative to other contexts, such as England with 65% (Humphreys et al., 2012).

There are potential threats associated with achieving productivity targets in relation to land drainage (Skaggs et al., 1994; Jacinthe et al., 2001). Soil moisture is a key driver that affects the accumulation and storage of C in soil. Globally, Jobbágy and Jackson (2000) found that soil C stocks are positively correlated with mean annual precipitation and negatively with mean annual temperatures. Thus, larger C stocks are found in latitudinal gradients with moist cold ecosystems and frequently saturated soils (Moyano et al., 2013) as is typical in the Irish context. Conditions where the water filled pore spaces of the soil is close to saturation results in the decreased metabolic activity of aerobic organisms as respiration rates are reduced due to oxygen deprivation and slow diffusion (Franzluebbers, 1999; Dessureault-Rompré et al., 2011). At its simplest drainage of very wet soils promotes aeration which results in the optimisation of microbial oxidation of organic matter and the release of carbon dioxide (CO_2) to the atmosphere (Kechavarzi et al., 2010; Willems et al., 2011; Necpálová et al., 2014; Burchill et al., 2014).

Objectives

In this paper, we examine the trade-offs between the soil functions 'primary productivity' and 'carbon cycling and storage', in response to the intervention of agricultural land drainage systems of imperfectly and poorly draining managed grasslands. Specifically, we examine these trade-offs as a function of the nominal price of Certified Emission Reductions (CER's) or 'carbon credits'. This is achieved whereby the economic value of productivity gains associated with the installation of land drainage systems is compared to a range of CO_2 prices. This is shown spatially to account for geographical variation. This paper therefore constitutes the first example of a practical application of the concept of Functional Land Management that is of direct relevance to policy stakeholders.

Materials and methods

Land use data

Schulte et al. (2014) related the relative functionality of soil functions in the first instance to land use (Fig. 1) and added that further categorisation is required in relation to soil drainage categories, which is the subject of current research (Coyle et al., in preparation). Fig. 1 shows that all soils deliver a suite of soil functions but the delivery of individual functions relies on land use. Although land drainage systems are installed across different drainage classes, we focus on poorly and imperfectly drained managed grasslands as these represent the vast majority of sites. Grasslands on soils with an organic layer of greater than 40 cm depth or on histic lithosols are not included in this analysis as drainage requirements for peat depend on the parent material underlying the peat layer; furthermore this relates to more long term projects that are commonly outside the scope of individual farmers (Tuohy et al., 2013). Therefore, as a first step in our spatial analysis, we needed to establish the location and geographical extents of land use in combination with the drainage classes poorly drained and imperfectly drained (Schulte et al., submitted for publication).

We used the following datasets:

- Land Parcel Identification Service (LPIS), Department of Food, Agriculture and the Marine – data show the farm outlines of all land held by farmers who have applied for support payments from the EU. Data are held electronically on the DAF mainframe and maps are updated annually by Mallon Technology since 1995 (Mallon Technology, 2014). Data were reclassified on the basis of the main land uses required to populate the matrix in Fig. 1. Any other listed land uses were classified as 'other'.
- Forest Service – since 1995 the Forest Service have produced spatial datasets detailing the extent of the forest estate in Ireland. The current dataset, Forest07, includes detailed species information. This information was placed in 'forest type' categories based on the Forest Type definitions using a standardised system of nomenclature adopted to classify forests based on the composition of tree canopy cover, available at: Forest Type Methodology (DAFM, 2013). This was further reclassified wherein all broadleaf and mixed forestry were combined into one category, coniferous stayed as an exclusive category and all remaining forestry was reclassified as other forestry 'OF' to be included in the 'other' land use category.

- Natura 2000 – The National Parks and Wildlife Service (NPWS) is responsible for the designation of conservation sites in Ireland and includes four categories: (1) SPA, special protection areas; (2) SAC, special areas of conservation; (3) NHA, national heritage areas, and (4) PNHA, proposed national heritage areas. Status definitions available at: Protected sites Ireland (NPWS, 2014). Natura 2000 is included as a land use as it represents an important indicator for Functional Land Management. Natura 2000 occurs on all land uses, and this designation defines the management options and the suite of soil functions available. Therefore, in our analysis we use Natura 2000 as a separate land use. Shapefiles were combined to provide one Natura 2000 data layer. Custom python script was used to overcome issues associated with duplicate geometry for sites of more than one designation.

We combined spatial datasets in ArcGIS 10.2.2 using overlay analysis, and maps were generated in Arc Map 10.2.2. Datasets were processed in polygon shapefile format allowing the calculation of geometry and spatial extents of land areas. Fig. 2 below shows the workflow schema for the datasets and results are shown in Fig. 3. All datasets were set to projected coordinate system (PCS) of the Irish National Grid TM65_Irish_Grid.

Soil drainage

To extend this and include soil type in addition to land use type, the land use data were overlaid with an indicative drainage map (Schulte et al., 2005, submitted for publication). The indicative drainage map is based upon the Irish Soil Information System National Soil Map of the Republic of Ireland, constructed at 1:250,000 (Creamer et al., 2014a). Importantly, land drainage works in Ireland typically are <10 hectares (ha) in size, where soils are heterogeneous and standardised drainage system designs are not appropriate as these are intrinsically site specific. Consequently, characterisation of Functional Land Management is generalised to a scale that is usable at a national policy level and is not suitable at a farm or local level. Based on the Irish Soil Information System, this scale is 1:250,000 which can account for spatial variability at a soil association level. Drainage categories were assigned on the basis of diagnostic features based on field based descriptions (Schulte et al., submitted). This enabled us to calculate the spatial extent of each drainage class for every land use category (Table 1). Poorly draining soils were defined as those showing mottling throughout the profile and have an argic or spodic horizon resulting in stagnation. Soils with much more than 40 cm of an organic layer are classified as peat. Moderately drained soils present mottling at depth, but lack any organic matter accumulation but an argic or spodic horizon may be present. Mottling at the same depth but with a presence of some organic matter accumulation and an argic or spodic horizon present were categorised as imperfectly drained. Well drained soils are those that showed no evidence of water-logging and have no argic or spodic horizon present. For the small number of soils where the presence of sandy loam or sandy textural classes is dominant, this soil subgroup was considered excessively drained. A detailed description of the diagnostic criteria will be published in Schulte et al. (submitted).

Carbon loss model

Biogeochemical modelling

We used a modified version of the DNDC model (version 9.4; see Li et al., 2011; Abdalla et al., 2013) to assess the impact of drainage on Irish soils. DNDC contains four main sub-models (Li et al., 1992; Li, 2000, 2011); the soil climate sub-model calculates hourly and daily soil temperature and moisture fluxes, the crop growth sub-model, the decomposition sub-model and the denitrification sub-model.

The model calculates soil organic matter sequestration from simulated organic matter turnover, crop growth (which simulates crop biomass accumulation and partitioning) and decomposition (which calculates decomposition, nitrification, ammonia (NH_3) volatilisation and CO_2 production through heterotrophic and autotrophic respiration). When grass is cut or grazed, all of the root biomass and a specified fraction of the stem biomass are added to the soil litter pool of carbon. C and nitrogen (N) inputs from agricultural management (i.e. animals and fertilisers) are also inputted via management and grazing sub-routines. Leached carbon is calculated from the hydrological model which simulates hydrological flows. The denitrification sub-model tracks the sequential biochemical reduction from nitrate (NO_3) to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and nitrogen (N_2) based on soil redox potential and dissolved organic carbon.

Daily measured values of meteorological parameters, management and soil properties were used as input variables to the DNDC model (see below). Field N_2O flux data were used for DNDC model validations by comparing previous measured and predicted gas fluxes (see Li et al., 2011). As soil C sequestration is sensitive to the distribution of C between recalcitrant and labile pools, the models were run for 200 years until soil C pools reached equilibrium. The model was then run with (a) the water table set near the surface (10 cm) (near saturated conditions which would represent and undrained scenario), and (b) with the water table depth dropped to 1.5 m below the surface (drainage system represents deepest piped drains possible). Both depths are chosen as representing the full range of conditions in relation to land drainage.

Parameters

- Synoptic station data – weather data from five main weather stations geographically spread across the republic of Ireland were used: (1) Valentia; (2) Malin Head; (3) Belmullet; (4) Mullingar, and (5) Dublin. Data were recorded by Met Éireann (the meteorological service of Ireland).
- Clay content values for drainage classes were defined using the modal series for soil types. Soils were categorised on the basis of drainage (well, imperfect and poor) and type (histic, humose or typical). Horizons were disaggregated to depths of 0–25 cm; 25–40 cm; 40–60 cm and 80 cm plus. The clay values by horizon for the different soil types were averaged to develop a clay horizon curve based on data analysed for the National Soil Map (Creamer et al., 2014a).
- The livestock density was set at two typical dairy cows per hectare (ha) with an implied organic manure deposition of 85 kg per animal and 170 kg ha^{-1}. These figures are above the average livestock density in Ireland, but typical for farms, predominantly dairy enterprises, that are currently installing drainage systems in anticipation of the abolition of EU milk quota. This livestock density also corresponds to the lower limit of the derogation requirement by Ireland pursuant to Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources to be sufficiently accounted.

Indicative carbon map for imperfect and poorly draining grasslands

The potential C loss was computed from the difference in soil C stocks associated with each of the modelled groundwater depth. We accounted for the spatial heterogeneity of soils by using the Irish Soil Information System, which provides an inventory of the diversity of soils and their properties as well as geographic extents (Creamer et al., 2014b). As a result, we produced an indicative soil

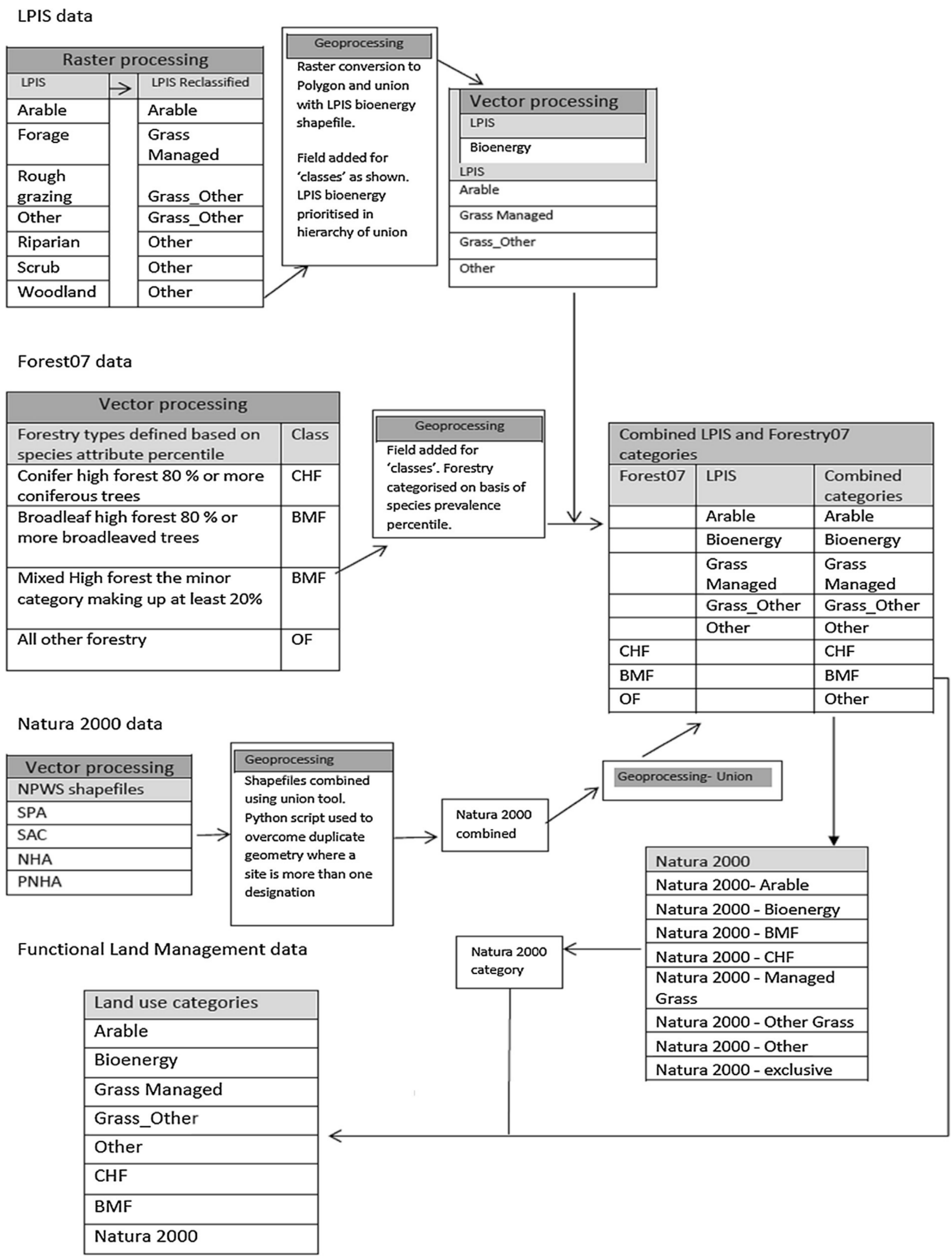

Fig. 2. Land use mapping data schema.

C loss map that, at an association level (1: 250,000), accounts for the spatial variation in the potential soil C loss. Output data from the C model was plotted indicating the soil organic carbon (SOC) (tonne C $ha^{-1}a^{-1}$) loss associated with drainage for both imperfect and poorly draining soils used for managed grass. These data were splined using a tension spline set at 0.1 and 4 points in ArcGIS 10.2.2 and converted to shapefile format. These steps were processed separately for the imperfectly draining and the poorly draining soils. Finally, these shapefiles were unioned to produce a combined indicative SOC loss map.

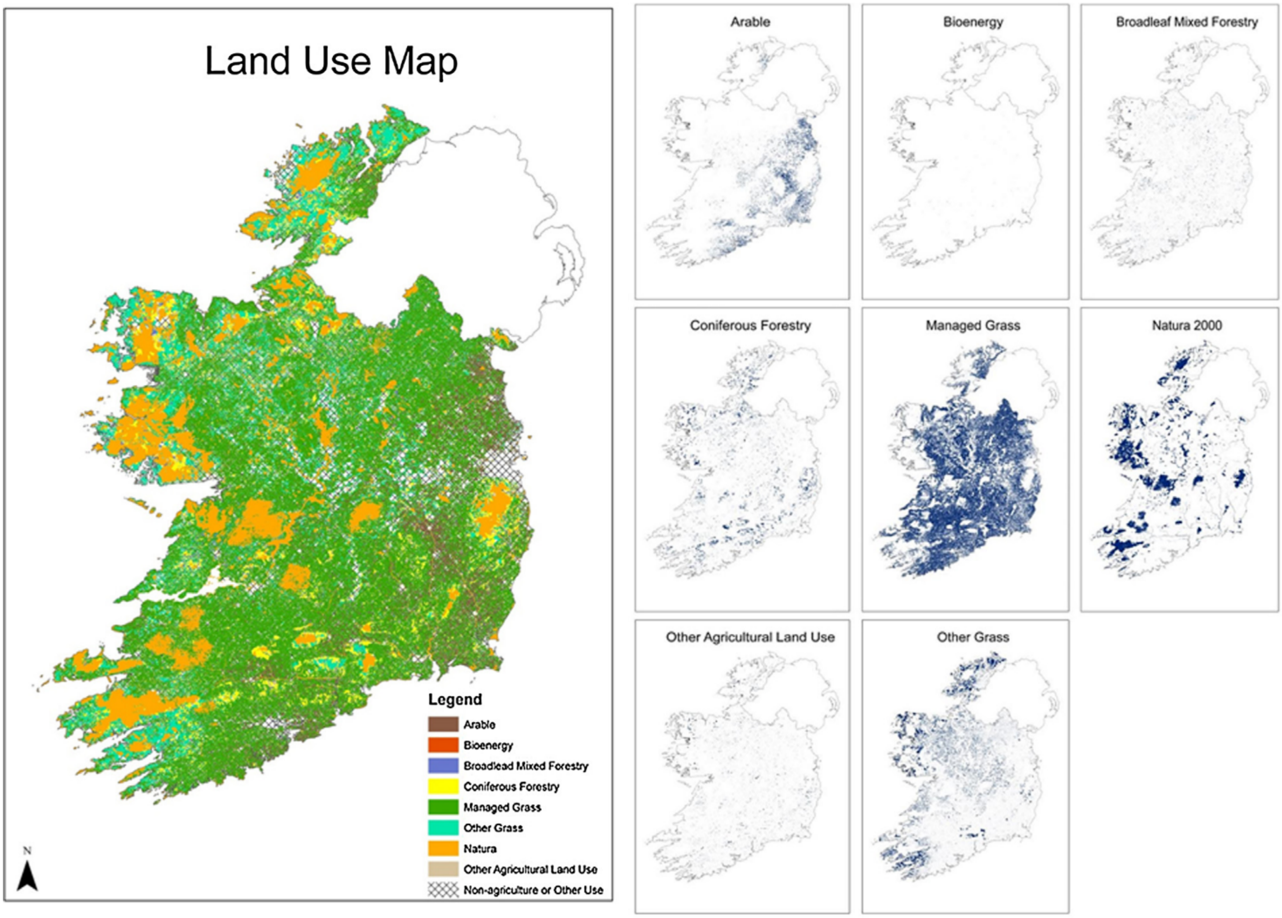

Fig. 3. Indicative land use map of Ireland.

Productivity data

The impact of drainage on productivity was approximated by computing the extent to which land drainage decreases the number of days at which soils are untrafficable (Schulte et al., 2012). In their review, Schulte et al. (2012) found that a variety of trafficability thresholds are used in the literature, ranging from 0 to 10 mm soil moisture deficit (SMD). For the purpose of this exercise, we used a threshold of 5 mm. Here, we assumed that land drainage moves soils from the poorly drained or imperfectly drained categories into the moderately drained drainage category, as defined by the Hybrid Soil Moisture Deficit model (Schulte et al., 2005). The Hybrid Soil Moisture Deficit model has been widely applied and is used at a national level by Met Éireann and is cited in more than 50 scientific papers. It has been extensively calibrated for Irish conditions. An important caveat in this regard, is that the extent to which land drainage could move from imperfectly or poorly draining category to the next drainage category is site specific and may not be accurate for some of the wettest soils. However, for simplicity we made the zero-order assumption that the drainage works would be appropriately customised to the site-specific drainage requirements. By doing so, we quantify the potential increase in trafficability for all drainage scenarios in Ireland. For 104 climatic weather stations operated by Met Éireann, we computed the daily SMD for a 30-year period from 1979 to 2008 for poorly drained and moderately drained soils. Subsequently, for each of these weather stations we derived the median number of field capacity (FC) days for both drainage categories. The difference between these two median values was taken as an indicative value for the increase in the length of time that the soil is trafficable, and hence the increase in the length of the potential grazing season.

Table 1
Land use with drainage category based on Irish Soil Information System (ha).

	Arable	Bioenergy	Broadleaf mixed forestry	Coniferous forestry	Managed grass	Other grass	Natura 2000	Other agricultural land use
Excessively	3631	35	200	91	10,499	803	3771	137
Well	160,589	961	42,238	61,420	1,287,372	93,010	71,495	28,290
Moderately	124,152	721	16,826	23,234	661,375	42,447	15,102	11,345
Imperfectly	8358	79	6345	22,383	157,985	44,611	54,698	6614
Poor	65,746	595	33,016	57,534	797,567	87,663	148,449	24,438
Peat	7605	101	48,272	171,572	236,938	456,646	478,529	47,642
Other[a]	1441	13	2649	2057	26,310	60,086	268,963	1536
Grand total	371,522	2505	149,546	338,291	3,178,046	785,265	1,041,005	120,001

[a] Includes mask, urban, tidal marine, rock, island.

Expressing this increase in herbage productivity and utilisation in economic terms, previous research (reviewed in Schulte et al., 2012) has shown that this longer grazing season translates into an increase in the gross margin of dairy farming of between €2.30 and €3.20 per cow per day (Shalloo, 2009; Kinsella et al., 2010). Here, we used €2.75 as the average within that range. Similar to the C loss model, we assumed an average stocking rate of two cows per ha, resulting in an increase in €5.50 per ha per day of increased grazing season.

The economic data were added to the productivity file which was plotted in ArcGIS 10.2.2 and splined using a tension spline set at 0.1 and 4 points to develop an indicative productivity shapefile for Ireland. Once converted to a shapefile this was unioned and clipped with the imperfectly and poorly draining grasslands to give the final productivity file.

Carbon maintenance versus land drainage

The indicative soil C loss map (Fig. 4a) was unioned in ArcGIS 10.2.2 with the difference in trafficability days map (Fig. 4b). When combined a field was added and the final hectare extent of each polygon was calculated.

To add the productivity value gains associated with drainage a field was added and populated as follows:

$$\text{Productivity value gain} = [\text{hectares}] \times [\text{days}] \times [€5.50]$$

To add the SOC loss value, a field was added and populated by calculating the value by:

$$\text{Annual SOC loss} = \frac{[\text{Final SOC value}]}{[\text{Discount rate30 years}]}$$

To quantify CO_2 emissions the C stock changes were converted to units of CO_2 emissions by multiplying the C stock change by a conversion factor 3.667 (US EPA, 2004):

$$CO_2\ \text{loss} = [\text{Annual SOC loss}] \times 3.667\ \text{conversion factor}$$

We calculated the value of CO_2 loss for each polygon by multiplying the area extent by a variable price:

$$CO_2\ \text{loss values} = CO_2\ \text{loss} \times [\text{hectares}] \times [\text{variable price}]$$

The differential value of soil functions was calculated as: the difference between drainage benefit and the variable C prices:

$$\text{Differential value of soil function} = [\text{Productivity value gain}] - [CO_2\ \text{loss value}]$$

Results

Spatial extent of land use

Fig. 3 represents the first coherent land use map that combines agricultural land use categories, as defined within the Functional Land Management concept. Irish agriculture is primarily a grass-based industry (Teagasc, 2014). In line with this, excluding Natura 2000 designated grass, 'managed grass' accounts for over half (53%) of the agricultural land area and when combined with the 'other grass' category accounts for two-thirds of this area (66%). Arable represents almost 377 kHa, which aligns with findings of the Teagasc Tillage Crop Stakeholder Consultative Group (TTCSCG, 2012). Bioenergy continues to be a minor land use (<1%), reflecting little change since the end of the government pilot scheme in 2009 to support the development of non-food energy crops (McDonough, 2010). Coniferous plantations represent a much larger portion of land area compared to the broadleaf mixed forestry, and this is consistent with the focus on commercial timber and pulp production largely composed of non-native conifers that grow quickly in temperate moist climates (Bosbeer, 2012).

Table 1 reflects the spatial extents of land uses in their respective soil drainage categories. This table, whilst providing an aggregate spatial extent of the suite of soil functions in relation to drainage categories, does not distinguish between soil types but this is the subject of ongoing research. Soils in the poorly, imperfectly and peat drainage categories combined make up almost half (49.19%) of the soil drainage categories in Ireland. As these categories are considered 'wet soils' this finding aligns with that of Humphreys et al. (2011) who proposed that drainage problems account for almost half of soils in Ireland. In their research, Creighton et al. (2011) found wet soil conditions are likely the most important limiting factor restricting grass utilisation on Irish farms. Notably, even on well-drained soils, the number of field capacity days (Van Orshoven et al., 2013) is the main constraint to herbage utilisation (Creighton et al., 2011; Schulte et al., 2012). Given that a majority of agricultural land use in Ireland (Table 1) is dedicated to grasslands, wet soil conditions represent a major limitation in Irish agriculture. In relation to forestry, 75% of coniferous forestry can be found on wet soils, 51% of which is found on the peat drainage category. Similarly, 59% of broadleaf and mixed forestry are found on wet soils. In contrast, a majority of arable production (78%) is found on the drier soil drainage categories.

Trade-offs within Functional Land Management – the case of carbon storage and productivity gains associated with land drainage

Fig. 4a shows the spatial variability of potential SOC (tonne C $ha^{-1}a^{-1}$) loss in response to the installation of drainage systems, with greatest losses observable in the north-western and coastal locations of the country. The spatial variability of the delivery of the productivity function is represented in Fig. 4b and shows that the greatest benefits associated with drainage in relation to productivity gains can be found mostly in the south-west. This aligns with on-going research in relation to 'heavy' soils that are found in the south-west region, where these areas are known to be negatively impacted economically, due to excess soil moisture conditions (O'Loughlin et al., 2012; Tuohy et al., 2015).

Fig. 5a illustrates that at today's international CO_2 price of €6 per tonne (Thomson Reuters, 2014) productivity gains by far exceed the monetary value of potential CO_2 losses for almost 100% of the total grassland area. In contrast, at €150 per tonne, as illustrated in Fig. 5d, productivity gains are exceeded by this nominal CO_2 value in almost all areas (99.9%). Fig. 6 below, shows this relationship as the proportion of wet grassland where the value of CO_2 exceeds the value of productivity gains.

Discussion

Model constraints

The explicit aim of this paper was to assess trade-offs between two soil functions, namely carbon storage and primary productivity, in response to a management intervention, in this case artificial land drainage systems. In the context of studying the impact of land drainage on GHG balance sheets, this paper only considers soil carbon cycling and storage as the pertinent soil function being examined. A full GHG analysis would involve a full life cycle analysis (LCA) that quantifies changes in nitrous oxide (N_2O) and methane (CH_4) emissions, as well as changes in productivity in order to account for land use and indirect land use effects, which was outside the scope of this study. Also the time period for the loss of SOC

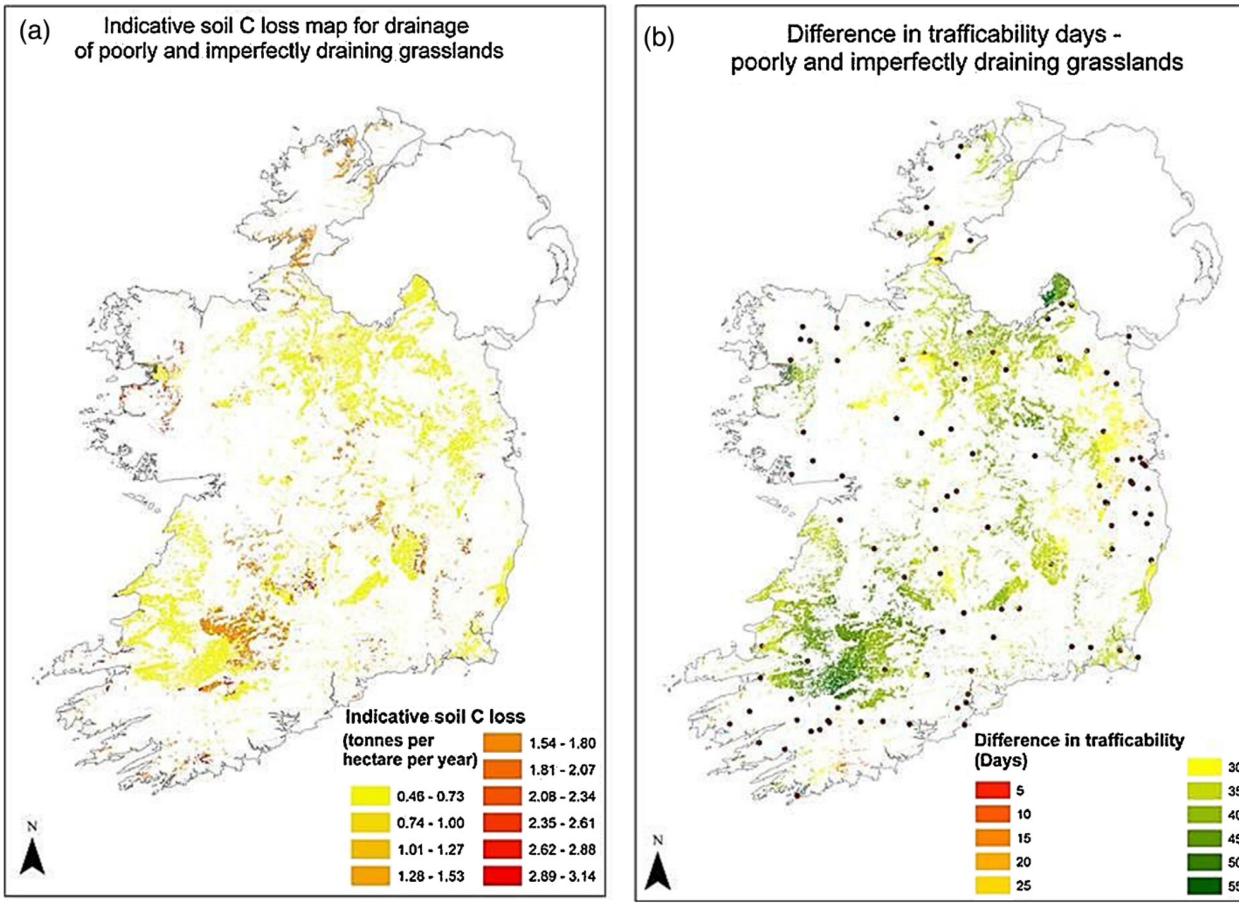

Fig. 4. (a) Indicative annual soil C loss for poorly and imperfectly draining grasslands in Ireland associated with drainage in one year, using a 30 year discount period. Data are categorised using equal intervals for illustrative purposes. (b) Difference in trafficability days for the same soils. The data for both figures were combined to compare (a) variable carbon price against productivity as defined by trafficability days.

was set at 30 years post-drainage. However, the impacts of land management on grassland soils can vary from 10 years to >100 years depending on (a) the magnitude of the disturbance and (b) the soil type and climate (Poeplau and Don, 2013). For similar reasons, we did not consider the capital costs associated with drainage systems in our economic analysis; instead, we constrained our analysis to the change in the value of the soil function 'primary productivity'. On a grassland site, specific drainage requirements and therefore design (spacing and depth) vary depending on soil physical parameters, site geometry and drainage criteria (rainfall minus evapo-transpiration). As a result, the current cost of a field drainage system ranges from €125 ha^{-1} for a shallow mole drainage system to €8600 ha^{-1} for the piped drainage conventional system (Anon., 2013). A cost benefit analysis, not based on empirical data, of the economics of land drainage for dairy systems has previously been quantified by Crosson et al. (2013) which found that where land drainage costs exceed €7413 ha^{-1} there is only economic benefit where grass growth increases by 30% at a milk price above 28 cent/l and 20% above 34 cent/l. These capital costs should be taken into account in the interpretation of Fig. 5. Where these costs are high, this will reduce the monetary value of gains in primary productivity, and will reduce the price of C at which these gains are equalled by loss in the value of soil C.

For the indicative soil C map, five synoptic weather stations were used, and although geographically spread across the country, this reflects a lower spatial resolution of the C model as opposed to the trafficability model which was based on daily data from 104 climatic weather stations. This difference in the number of weather stations used for the two maps is consistent with the difference in resolution or precision between the C model and trafficability model, with the latter having been extensively calibrated, validated and used, specifically under Irish conditions: this allowed for a greater resolution in input data.

We arbitrarily set the threshold for trafficability at 5 mm of SMD, this being the middle of the range of thresholds reviewed by Schulte et al. (2012). Our experience with the Hybrid Soil Moisture Deficit model is that this is also the range at which the model predictions on SMD diverge most prominently between drainage categories: the model converges when the SMD approaches either 0 mm or exceeds 10 mm.

Sensitivity analysis

We based our analyses on a discount period of the soil C losses of 30 years following the installation of drainage systems. However, the rules governing the accounting of the Land Use, Land Use Change and Forestry (LULUCF) sector are currently under development and subject to change. In Fig. 7, we present a sensitivity analysis in relation to both the nominal CO_2 price and the discount rate over which the loss of SOC is applied for reporting purposes. The results show a high degree of sensitivity to the discount period. At a discount rate of 10 years the increased value of productivity could be outstripped by the environmental value of CO_2 loss almost at a carbon price as low as €40 per tonne. In contrast, when we apply a discount period of 40 years at the same price, productivity gains exceed CO_2 value in almost all areas.

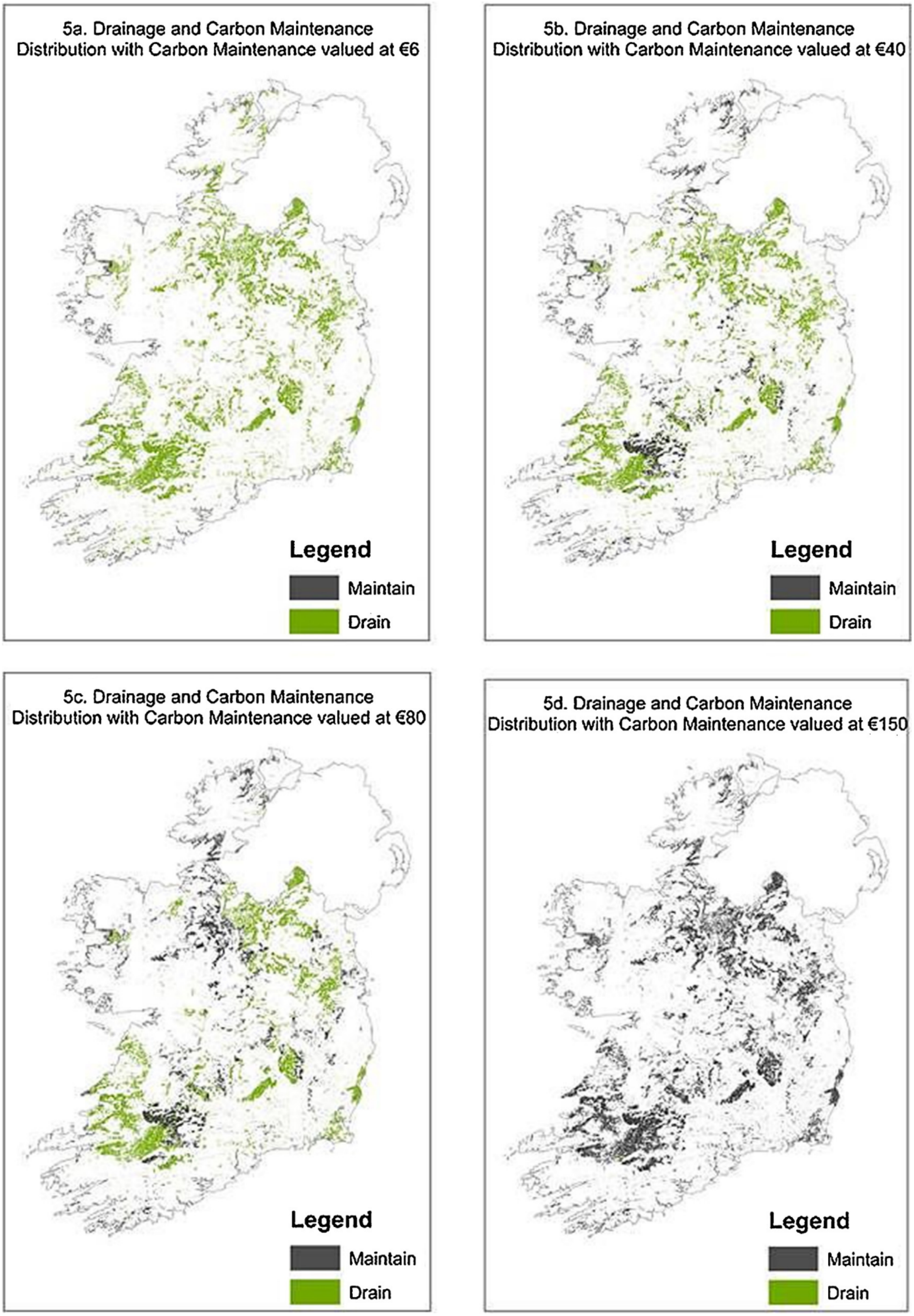

Fig. 5. (a–d) Drainage and carbon maintenance distribution relative to C values ranging €6–€150.

Trade-off between soil functions 'primary productivity' and 'carbon cycling and storage'

Using Ireland as a case-study, we explored the trade-offs between the two soil functions. Specifically, we examined these trade-offs as a function of the nominal price of 'carbon credits'. This trade-off has been demonstrated spatially using a range of C prices (Fig. 5a–d). In relation to the delivery of soil functions it is essential to understand how individual soil functions are prioritised. In particular, it is necessary to understand the perspectives of those

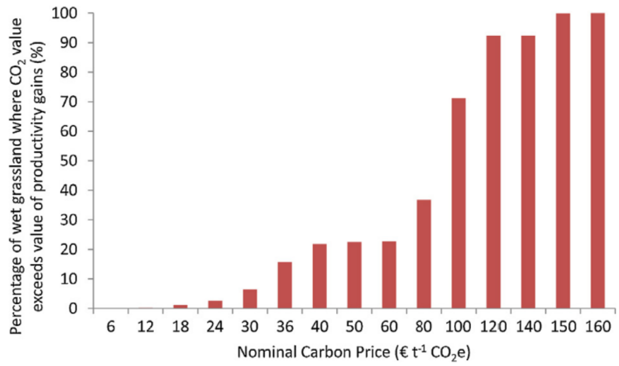

Fig. 6. Proportion of poorly and imperfectly drained grasslands on which the value of soil carbon loss is projected to exceed the value of productivity gains, in response to the installation of drainage systems.

that are responsible for the delivery of the supply of soil functions (generally farmers and foresters), and those that frame demand for soil functions (i.e. policy makers).

Farmers value primary productivity as it directly affects farm income. Land drainage offers increases in productivity potential. At the scale presented in this study, the research indicates that land drainage could potentially increase the trafficable period by as many as 55 days per year (Fig. 4b), which translates to productivity gains of €302.50 ha^{-1} a^{-1}. Based on current CO_2 prices of €6 per tonne (Thomson Reuters, 2014), Fig. 6 shows that the value of these gains in productivity exceed the "carbon cost" on almost 100% of the grasslands in the study. For farmers, the environmental cost does not translate into a change in income, or into a direct and observable change in the quality of the countryside, especially at today's CO_2 price. Even if future CO_2 prices were to increase to €40 tonne, this finding still holds true for almost 80% of the relevant area.

In contrast, the C cycling and storage function of soils is a high priority for policy makers who are focused on reducing EU GHG emissions. To this stakeholder group, land drainage may represent a potential threat. Whilst recognising the agronomic opportunity cost in relation to decisions to forego land drainage, they may consider this cost small compared to the long-run environmental cost.

Our paper shows that these divergent perspectives can be explained, at least partially, by the different monetary values that these two stakeholder groups assign to soil organic carbon. EU Commission, developing a policy for 2030, bases their assessments on the projected CO_2 price by 2030, which they set at €40 per tonne CO_2 (EC, 2014a). Allowing for an inflation rate of 2% per annum, this would equate to a value of €30 per tonne in today's money. Based on these assumptions, Fig. 5 indicates that should this higher CO_2 price materialise by 2030, the environmental cost of C loss would outstrip the financial benefits of increased production for 21.78% of the area at a discount rate of 30 years. CO_2 loss would only exceed productivity gains at either higher CO_2 prices, or at reduced discount rates (e.g. 10 years) that are currently being considered. Fig. 7 demonstrates that the outputs are indeed very sensitive to the discount period rate.

At this point, it is unclear to what extent the C price can be managed or manipulated to incentivise maintenance of soil C stocks. Currently, this price is determined by the international market price. GHG emissions from agriculture are aggregated at national scale and any compliance or non-compliance with EU targets is burdened by the national exchequer. Opportunities for farm-level incentivisation are limited: two key issues emerge in this regard. In the first instance, the rules of EU agri-environmental schemes under the Common Agricultural Policy (CAP) Pillar II only allow for actual costs to be remunerated. The calculation of premia for EU funded schemes is derived on the basis of costs incurred and income foregone by the farmer in the participation of the agri-environmental measure (Murphy *et al.*, 2013). Not draining land does not represent an actual cost, but is instead an opportunity cost and as such is not eligible to be included under Pillar II payments (Murphy et al., 2013). Secondly, monitoring, reporting and verification (MRV) or carbon-auditing at a farm scale are associated with significant operational challenges that include high administrative transaction costs, low accuracy, issues of equitability (Teagasc, 2011b).

In conclusion, this research highlights that in relation to 'primary productivity' and 'carbon cycling and storage' a considerable gap exists in relation to the prioritisation of these soil functions from two diverging stakeholder perspectives. Whilst the current CO_2 price fails to incentivise the maintenance of SOC stocks this equation is likely to change, depending on the discount period applied in MRV of the LULUCF sector. Moreover, the metrics used for EU funded schemes would require more flexible mechanisms that could also take account of opportunity costs.

Functional Land Management for supporting targeted policies

Forest and agricultural land currently covers more than three-quarters of the EU territory and naturally hold large C stocks (EC, 2014b). The release of just 0.1% of the C stored in these soils would equal the annual emissions from 100 million cars (EC, 2014c). In Ireland, despite a downward trajectory in carbon emissions since 2005, agriculture still accounted for 40% of the non-ETS emission and 30% of all GHGs in 2011 (Farrelly et al., 2014). Within the EU, expanding on previous climate and energy packages, European leaders have committed to reductions in both the emissions trading sector (ETS) and the non-ETS amounting to a 43% and 30% reduction by 2030 compared to 2005 respectively (European Council, 2014). Given the size of the agricultural sector in Ireland, and its contribution to GHG emissions, any meaningful reduction in GHG emissions will require a marked reduction in agricultural emissions.

Where a divergence in the prioritisation of soil functions exists, such as was highlighted here, a need to harmonise and incentivise the delivery of soil functions to meet multiple objectives exists. Here, we performed a sensitivity analysis at a range of C values in relation to biophysical criteria at a scale that is potentially usable for policy makers in constructing a realistic value to satisfy the demand for an individual soil function, in this case C cycling and storage, in relation to the primary productivity function. Moreover, we performed a sensitivity analysis in relation to variable discount periods, the results of which yielded a high degree of sensitivity to the discount rate. Both of these, enable policy makers to develop agri-environmental policies that support the optimisation of soil functions by contrasting the potential trade-offs between soil functions. This would allow soil functions to be altered in such a way that some functions can be incentivised or suppressed. At a time of ever increasing demands on the soil resource, the Functional Land Management framework can facilitate the development of land use policies that are more harmonised and result in land use management decisions that better reflect policy goals and targets. The spatial analysis presented in this paper enabled the characterisation of the spatial dimension of the complex interaction between land use and biophysical constraints/endowments, as defined by soil drainage categories. The Functional Land Management framework thus allows for the development of policies that are specifically tailored to contrasting biophysical environments, and are therefore potentially more effective than 'blanket approaches'. By design, Functional Land Management is not intended to be a legislative instrument for the 'zoning' of land use, but rather a tool to support policy decision

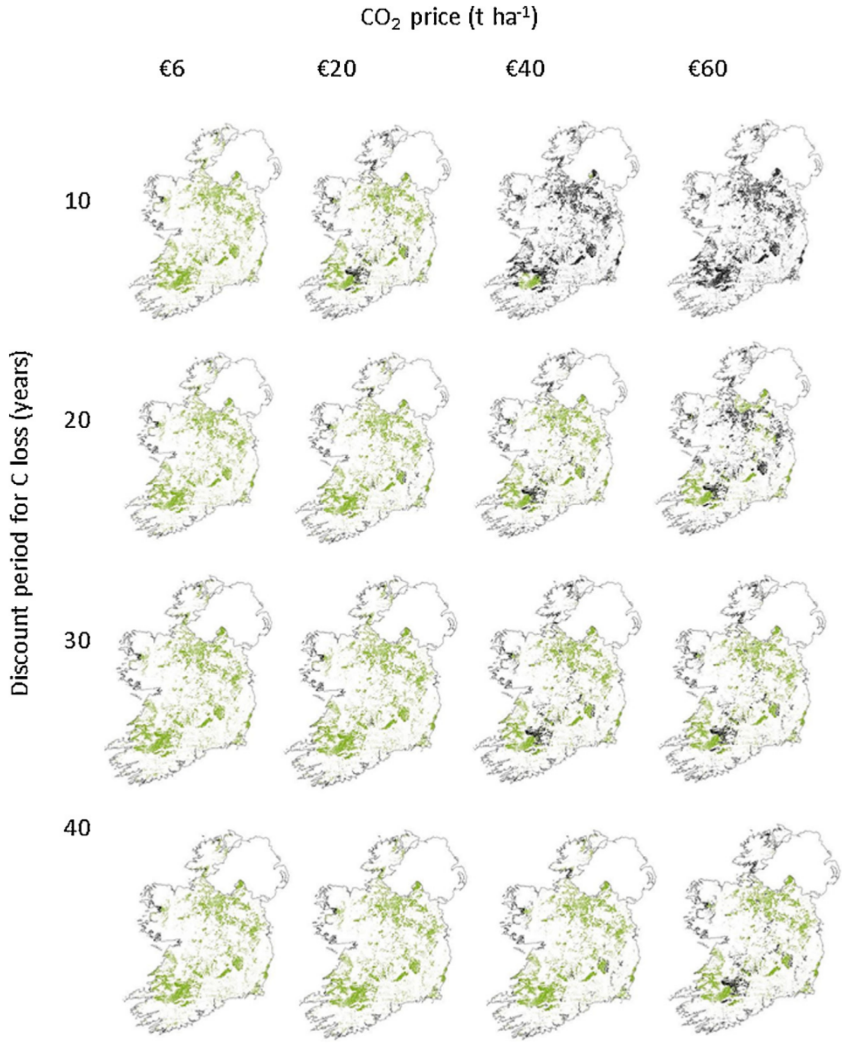

Fig. 7. Drainage (green) and carbon maintenance (black) distribution as a function of the nominal value of carbon and variable discount periods ranging from 10 to 40 years.

making that incentivises appropriate land management decisions (O'Sullivan et al., 2014; Schulte et al., 2014).

Whilst this research is focused on the development of Functional Land Management as a tool for national or regional policy formation, it is important to briefly consider how national target setting relates to changes in management practices at farm level and vice versa. Notwithstanding the challenges associated with translating a national objective into an agricultural cost or incentive, synergies exist between national and farm level priorities. The success of Ireland's significant food exports is intrinsically linked to the green credentials associated with management practices at farm level. It is a contemporary imperative to demonstrate and further improve the C efficiency of production to maintain these credentials (Murphy et al., 2013). Farm level tools, such as the Carbon Navigator that measure and guide adoption of technologies to reduce GHG emissions on farms, provide one mechanism to support this. It is important that such tools are flexible and can incorporate new research findings, for example in relation to decision making on drainage. As such, these tools can then provide a pathway to connect national policy objectives to on-farm decision making.

Further research

As a first example of Functional Land Management, we have investigated the impact of a manipulation of soil functions by direct alteration of soil properties. Therein, this study provides one example of the trade-offs between two soil functions. Further research would seek to build on this case study by exploring trade-offs in relation to the delivery of the other soil functions: water purification, habitat and nutrient cycling in response to land drainage interventions. In relation to the technicalities of land drainage, there remain knowledge gaps in relation to spatial extent of different types of drainage systems and further investigation could expand on and refine the current model. Equally, it is important to investigate further opportunities for synergies between national level target setting and on-farm management practices and develop pathways to connect these two.

Conclusions

- We have explicitly quantified an example of the trade-offs between two soil functions: primary productivity and C cycling and storage.
- We used drainage systems for this example: these can increase productivity by up to €302.50 ha^{-1} a^{-1}, but decreases soil carbon stocks.
- We showed that the prioritisation and incentivisation of these competing soil functions is primarily a function of the CO_2 price.
- At the current CO_2 price, the agronomic benefits are larger than the monetised environmental costs. This results in an incentive for farmers to drain.

- Even at future projected prices, this finding remains true for almost 80% of the land area however this is highly dependent on the discount period.
- Should the discount period be reduced to ten years could result in an inverse observation materialising. This scenario could result in incentives for policy makers and legislators to discourage the installation of drainage systems.
- Finally, our study shows large geographic variation in this environmental cost: agronomic benefit ratio. This allows for more specific and hence effective prioritisation of the two contrasting soil functions.

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